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Aptian carbonate platform development in the Southern Iberian Palaeomargin (Prebetic of Alicante, SE Spain)☆

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Abstract – The Aptian stratigraphic record of the Alicante region consists of: a rudist and coral-rich carbonate platform of earliest Aptian age (Llopis Formation), with a discontinuous siliciclastic member at its top; followed by late Early, to Late Aptian hemipelagic marls and marlstones (Almadich Formation); and then by renewed carbonate platform development of Late Aptian to earliest Albian age (Seguilí Formation). In the Llopis Formation, SW-dipping, massive clinoform beds of bioclastic debris are succeeded by flat-lying platform-top beds. The latter show a cyclically regressive stacking of biofacies, with rudist-dominated floatstone in their lower parts passing upwards to finer-grained, more sparsely fossiliferous bed tops with burrow mottling. Caprinid rudists, with originally almost wholly aragonitic shells, dominate the external platform-top facies, while more internal facies contain a mix of monopleurid, polyconitid and requieniid rudists, all with relatively slightly thicker development of the calcitic outer shell layer, together with caprinids. Biostratigraphic and carbon-isotope data link the termination of the Llopis platform with the onset of OAE1a. The carbonate platform of the Seguilí Formation again contains tabular platform-top beds showing repeated cyclic regression, with dense rudist and/or chondrodont floatstones overlain by sparser floatstones with wackestone matrix and secondarily filled burrows. But caprinids are now absent, while requieniids and polyconitids, some of large size, as well as radiolitids, all with thickened calcitic outer shell layers, accompany the tubular monopleurid, *Mathesia*, together with a greater development of *Chondrodonta* biofacies. The same overall pattern of biotic turnover from the Early, to the Late Aptian is confirmed in other parts of Iberia and contiguous regions. Moreover, Iberian platforms of late Early Aptian age outside the present study area reveal a transitional phase with an increasing proportion of polyconitids in the outer platform-top to upper slope facies at the expense of caprinids. The siliciclastic influx at the top of the Llopis Formation implies a climatic shift from arid, to relatively more humid/pluvial conditions through the mid-Early Aptian, as seen in several other Iberian sections. This climatic change was probably forced by the intensified greenhouse conditions at the onset of OAE1a. By contrast with these Iberian platforms, caprinids continued to dominate the outer platform-top zones of some central to southern Tethyan platforms until the close of the Early Aptian. This broad palaeolatitudinal differentiation of rudist associations within the Tethyan belt implies a climatic influence, whether exerted through thermal modulation of seawater pH and/or aragonite saturation, variation in nutrient flux, or any combination of these.

Keywords: Aptian / carbonate platforms / Prebetic Zone / palaeoecology / rudist coral formations / OAE1a

Résumé – Développement des plates-formes carbonatées dans l'Aptien de la marge continentale sud-Ibérique (Prébétique d'Alicante, SE d'Espagne). L'enregistrement stratigraphique de l'Aptien de la région d'Alicante comprend successivement une plate-forme carbonatée à rudistes et coraux abondants dans l'Aptien basal (Formation de Llopis), un membre silicoclastique discontinu à son sommet, des marnes hémipélagiques jusqu'à l'Aptien supérieur (formation d'Almadich), puis via un développement renouvelé, une plate-forme carbonatée datée de l'Aptien tardif à Albien basal (Formation de Seguilí). Dans la formation de Llopis, des clinoformes massifs à débris bioclastiques, inclinés vers le SW, sont surmontés par des lits horizontaux au toit de la plate-forme. Ces derniers montrent un empilement de biofaciès cycliquement régressifs, comprenant des *floatstones* dominés par les rudistes dans leur partie inférieure, puis enregistrent

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vers le haut une diminution de la granulométrie et des macrofossiles et enfin, des marbrures de terriers au sommet. Les rudistes caprinidés, aux coquilles à l'origine presque entièrement aragonitiques, dominent le faciès externe du toit de la plate-forme, tandis que les faciès internes contiennent un mélange de rudistes monopleuridés, polyconitidés et requiéniidés. L'ensemble de ces rudistes montrent un développement relativement plus épais de la couche externe calcitique par rapport à celle des caprinidés. Les données biostratigraphiques et isotopiques établissent un lien entre la fin de la plate-forme Llopis et l'apparition de l'OAE 1a. La plate-forme carbonatée de la formation de Seguilí comprend à nouveau des lits tabulaires à son sommet, correspondant à des régressions cycliques répétées, avec des *floatstones* denses à rudistes et/ou à chondrodontes, recouverts par des *floatstones* plus clairsemés à matrice wackestone présentant des terriers secondairement remplis. Il est à noter l'absence des caprinidés. Les requiéniidés et les polyconitidés dont certains sont de grande taille, ainsi que les radiolitidés, tous dotés d'épaisses couches superficielles de calcite, accompagnent le monopleuridé tubulaire *Mathesia*, ainsi qu'un développement plus important des biofaciès à *Chondrodonta*. Le même schéma général de renouvellement biotique du début à la fin de l'Aptien est confirmé dans d'autres secteurs de la péninsule ibérique et des régions contiguës. De plus, les plates-formes ibériques du sommet de l'Aptien inférieur, situées en dehors de la zone d'étude, révèlent une phase de transition caractérisée par une proportion croissante de polyconitidés dans le faciès extérieur de la plate-forme et au sommet de la pente supérieure, aux dépens des caprinidés. L'afflux siliciclastique au sommet de la formation de Llopis implique un passage climatique des conditions arides à des conditions relativement plus humides/pluviales à la partie moyenne de l'Aptien inférieur, comme dans plusieurs autres sections ibériques. Ce changement climatique a probablement été forcé par l'intensification des conditions de serre au début de l'OAE1a. Contrairement à ces plates-formes ibériques, les caprinidés ont continué à dominer les zones les plus à l'extérieur des plates-formes de certaines plates-formes du centre au sud de Téthys jusqu'à la fin de l'Aptien inférieur. Cette large différenciation paléolatitudinale d'associations à rudistes au sein de la ceinture téthysienne implique une influence climatique, qu'elle soit exercée par modulation thermique du pH de l'eau de mer et/ou de la saturation en aragonite, soit par la variation du flux d'éléments nutritifs, ou soit par une combinaison de ces facteurs.

Mots clés : Aptien / plates-formes carbonatées / Zone Prébétique / paléoécologie / formations à rudistes et coraux / OAE1a

1 Introduction

Within the broad context of interest in the greenhouse world of the Cretaceous, considerable attention has been paid to the remarkable oceanic, climatic and biotic changes that occurred during the Aptian, including the episodic growth and demise of Tethyan carbonate platforms. Naturally, there has also been much discussion concerning controls on these changes, particularly the (still controversial) idea of a possible causal linkage with perturbations of the global carbon cycle. Hence, there is an ongoing need for high resolution stratigraphical investigations of comparatively complete basin to platform sections, to determine as precisely as possible the relative timing and palaeogeographical record of events in order to constrain or test explanatory models (Skelton *et al.*, 2012; Naafs *et al.*, 2016). Such is the basis of Spanish Government research project CGL2014-55274-P, "El Aptiense del Prebético: Cambios ambientales, bióticos y factores de control", involving detailed analysis of newly drilled cores in a hemipelagic section (Cau, Alicante Province) and biostratigraphical and palaeoecological logging of adjacent carbonate platform successions. This paper focuses on documenting changes in the macrobiotic biofacies constitution of the carbonate platforms, especially with respect to their dominant macrofossil constituent, the rudist bivalves.

The two main platform developments in the study area chronostratigraphically encompass the early part of the Early Aptian (lower Bedoulian middle to upper Llopis Formation) and the late Late Aptian to earliest Albian (upper Gargasian to lower Albian Seguilí Formation). In a final discussion section, we also review the macrobiotic constitution of selected platform developments outside the study area that represent the intervening late Early Aptian interval elsewhere in Spain, in order to characterize the pattern of faunal turnover in Iberian platforms throughout the Aptian. Finally, we consider possible controls on these biofacies changes.

1.1 Geological setting

The External Zones of the Betic Cordillera (Fig. 1a) are made of sedimentary units deposited on the Southern Iberian Palaeomargin (SIP) during the Alpine tectonic cycle (Triassic to early Miocene) (García-Hernández *et al.*, 1980; Vera, 2001, 2004). North of the Cordillera, Prebetic para-autochthonous units deposited on the SIP were overthrust by Subbetic allochthonous units that had accumulated in the pelagic domains to the south.

The initiation of seafloor spreading in the North Atlantic, which started very early in the Cretaceous, led to a decrease in the sinistral movement between Iberia and Africa that had prevailed during part of the Jurassic (Ziegler, 1988), and to a phase of rapid anti-clockwise rotation of Iberia relative to Europe that would culminate in seafloor spreading in the Bay of Biscay from middle Aptian times onwards (Olivet, 1996; Vergès and García-Senz, 2001). A more recent study (Tugend *et al.*, 2015) suggests an alternative model to the rapid anti-clockwise rotation, consisting in a north-south divergence between Europe and Iberia, leading to a polyphase propagation of the extensional regime affecting both the Atlantic Ocean and the Alpine Tethys systems. In whichever geodynamic

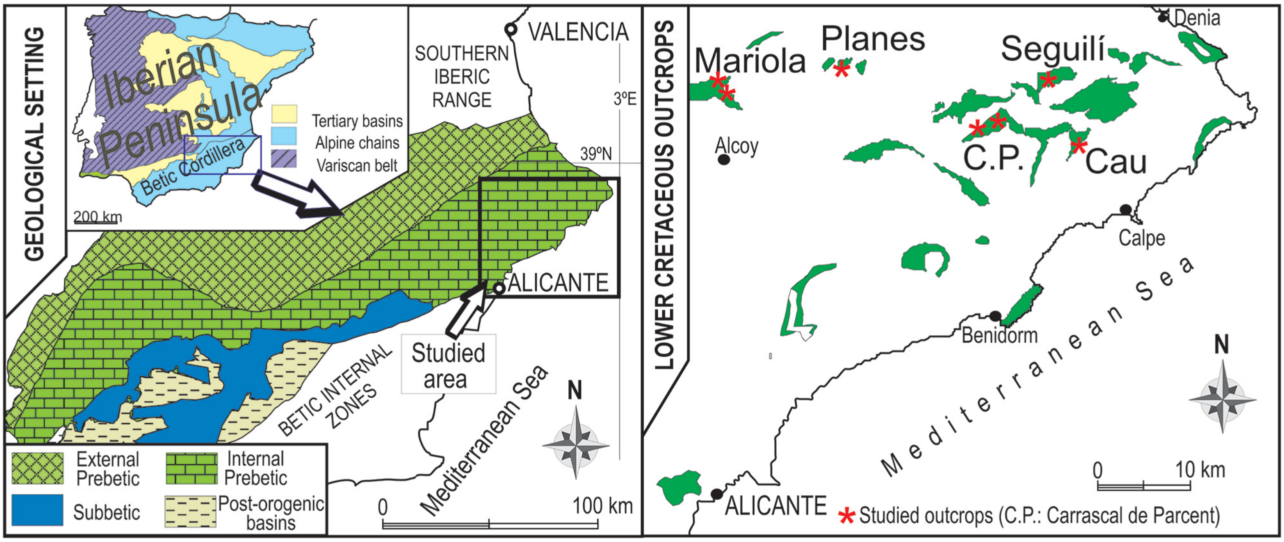

Fig. 1. Geographical and geological location of the studied sections: a: geological setting of study area in Iberia; b: studied outcrops.

framework was operative, extensional tectonics prevailed in the SIP. That extensional tectonism experienced a strong phase during the latest Jurassic to the Hauterivian, followed, during the Barremian–Aptian, by an interval of lesser tectonic movements but larger subsidence rates, which favoured the development of wide and thick carbonate platforms (including the Urgonian facies) in the shallow areas of the basins (García-Hernández *et al.*, 1980; Vilas *et al.*, 2001; García-Hernández *et al.*, 2001, 2003; Martín-Chivelet *et al.*, 2002; Vera, 2004; Castro *et al.*, 2008).

Basin analysis of the Prebetic platform (Vilas *et al.*, 1993; Martín-Chivelet *et al.*, 2002), has allowed the characterisation of the Early Cretaceous tectonosedimentary evolution of the Prebetic area, which was controlled by persistent, multi-episodic, extensional tectonics until the late Albian, when tectonic subsidence gave way to a generalized, complex, thermal subsidence. Within this interval, the Aptian represents a main tectonosedimentary episode (K4, Martín-Chivelet *et al.*, 2002; Alonso-Chaves *et al.*, 2004), bounded by two major discontinuities linked to extensional tectonic events that resulted in significant changes in basin palaeogeography and subsidence patterns. This Aptian tectonosedimentary episode corresponds to a second-order sedimentary cycle in the sense of Hardenbol *et al.* (1998), composed of a succession of third-order cycles that define a general transgressive-regressive evolution (Castro, 1998; Ruiz-Ortiz and Castro, 1998; Castro *et al.*, 2008).

During the Aptian, carbonate and siliciclastic sedimentation alternated in the proximal parts of the Prebetic, whereas towards the more distal parts of the platform, well represented in outcrops in the province of Alicante, shallow-marine carbonates and hemipelagic sediments alternate, representing the transition towards basinal settings (Castro *et al.*, 2008).

The Aptian stratigraphic record of the Prebetic of Alicante is represented by three formations, defined from the Alicante outcrops (Castro, 1998): the Llopis Formation, made up of shallow marine limestones with rudists and corals, locally with a siliciclastic member at its top (Lower Aptian of early Bedoulian age), the Almadich Formation, composed of hemipelagic marls and marlstones (Lower-Upper Aptian of late Bedoulian to early Clansayesian age) and the Seguilí Formation, with shallow marine limestones (Upper Aptian-lowermost Albian of late Gargasian to earliest Albian age) (Fig. 2). The boundaries between these formations are diachronous, as the Almadich Formation records a longer time interval towards more distal, southern locations.

The main sections investigated in this study (Mariola, Planes, Seguilí, Barranco de Alcaida and Casetas del Mayor) are located in the north of the province of Alicante (Fig. 1b), and their stratigraphy, biostratigraphy and sedimentology have been previously presented in several publications by two of the authors of this study (Castro and Ruiz-Ortiz, 1995; Ruiz-Ortiz and Castro, 1998; Castro, 1998; Castro *et al.*, 2008, 2014).

2 The Aptian carbonate platforms

2.1 Earliest Aptian Llopis Formation platform

2.1.1 Sierra de Mariola

The most stratigraphically extended development of the Llopis Formation crops out on the imposing north-eastern flank of the Sierra de Mariola (Fig. 3) in the north-western corner of the study area, where it reaches 210 m in total thickness (Castro, 1998; Castro *et al.*, 2008; Martínez-Rodríguez *et al.*, 2018). A mixed siliciclastic/carbonate lower member, some 50 m thick (not shown in Fig. 2 and not considered further in this work), of Late Barremian age and containing scattered rudist debris (Fig. 4a), is locally exposed on the eastern lower slopes of the sierra. This unit is succeeded by the coral- and rudist-rich basal units of the main, carbonate-dominated (Urgonian facies) middle member, of earliest Aptian age (Fig. 2). The cliffs below and to the SSW of the old ruins of Llopis Farm provide spectacular exposures of large-scale progradational bedding geometry in the upper part of the Llopis Formation middle member, consisting of SW-dipping, massive clinoform beds of bioclastic debris overlain by flat-lying platform-top beds (Fig. 3).

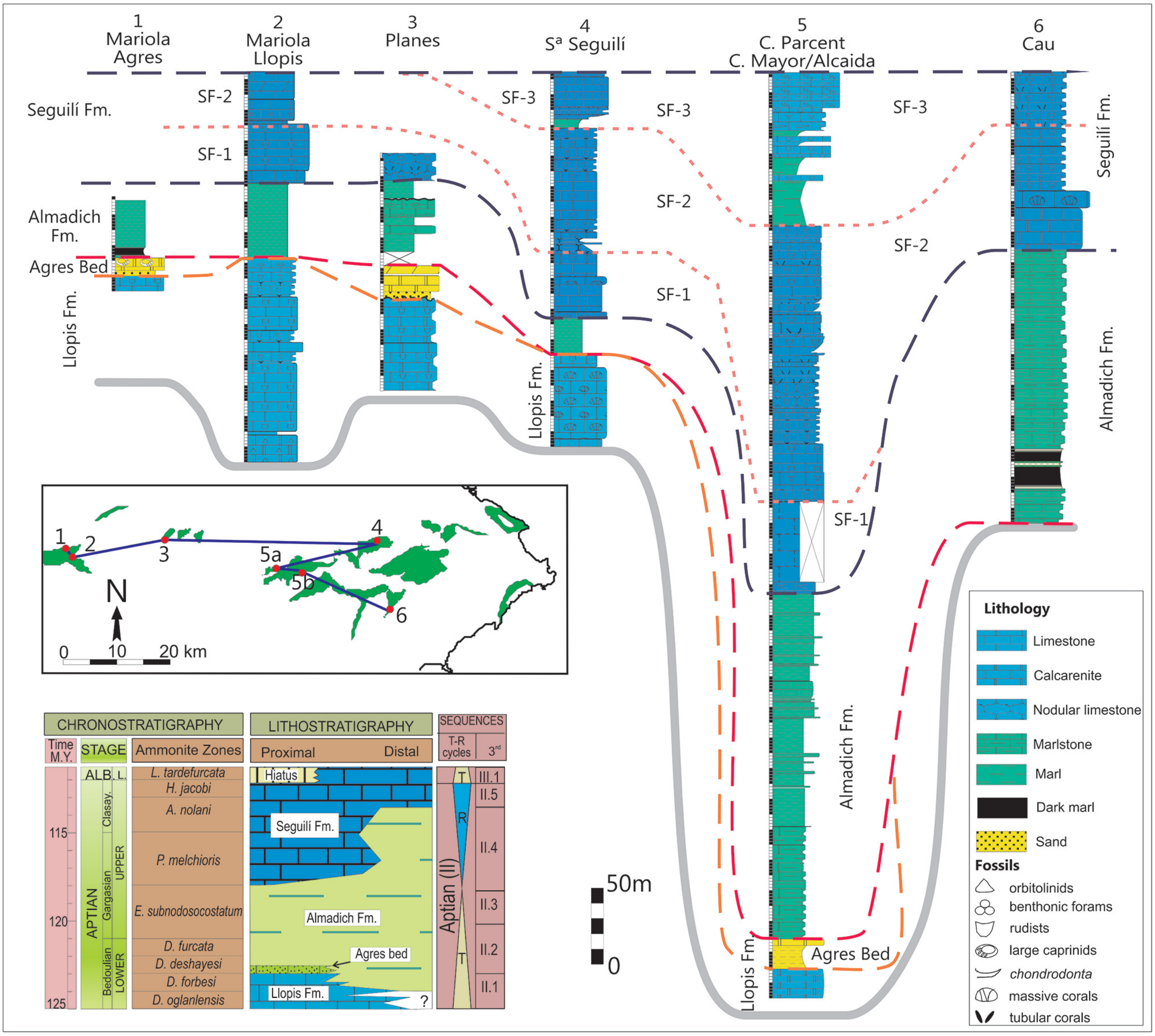

Fig. 2. Synoptic stratigraphical chart of the Aptian of the Alicante region, with location of investigated sections and chronostratigraphy. The Cau section (de Gea *et al.*, 2003; Naafs *et al.*, 2016) is included as a reference for the expression of OAE 1a.

The predominant facies in the upper clinoform beds are pale buff-grey coloured, fine- to coarse-grained bioclastic/peloidal wackestones to grainstones (Fig. 4b), with coarser, miliolid-rich burrow fills visible in places. Limited patches of floatstone contain whole and fragmented macrofossils, especially chondrodontid and rudist bivalves (Fig. 4c), together with benthic foraminifers and fragments of phaceloid corals, dasycladacean algae, crinoids and bryozoans, as well as intraclasts and some quartz. Some *Chondrodonta* are preserved in upright life position, attached to other shell debris, but otherwise, most of the benthic biota had evidently been more or less transported prior to deposition. A more distal equivalent of the Llopis Formation slope facies is exposed in a road section just over 30 km to the ESE, at Casetas del Mayor in the Carrascal de Parcent Sierra (Fig. 2): there, coarse grainstones contain well-rounded rudist and other shell debris (Fig. 4d).

The platform-top beds exposed in the cliff sections at Sierra de Mariola (Fig. 3) are mostly each over 2 m thick and contain pale grey bioclastic packstones and grainstones. Cyclic stacking of biofacies within these beds is common, with rudist-dominated floatstone (Fig. 5a) in their lower parts – though also including local clusters of slender elevator rudists preserved in upright life position (Fig. 5b) – passing upwards to finer-grained, more sparsely fossiliferous bed tops, which may show burrow mottling (Fig. 5c). The biota of these beds is similar to that in the upper clinoform beds, the main difference being the relatively greater abundance of rudists, including autochthonous examples, in the platform-top beds. However, pervasive leaching of the originally aragonitic inner shell of the rudists towards the top of the Llopis Formation makes identification problematical in many cases.

Some thinner cyclic beds exposed on the narrow plateau to the NNE of Llopis Farm expose more internal, predominantly

Fig. 3. Sierra de Mariola (see Fig. 1 for location): view towards SE along eastern face of the sierra, SSW of Llopis Farm (out of view to right), showing the middle member of the Llopis Formation in the foreground. Note depositional contrast in dip between clinoform beds (cb), below, and platform-top beds (pb), above.

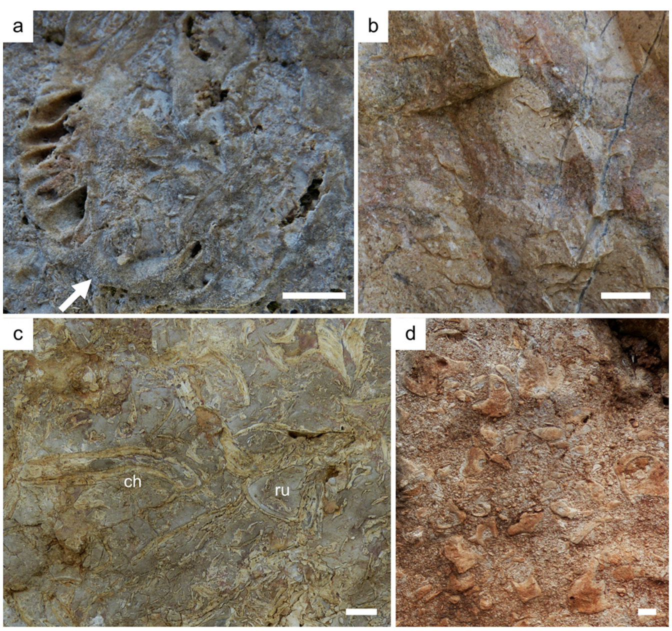

Fig. 4. Llopis Formation slope facies. (a-c) Sierra de Mariola: a: float from lower member, containing fragment of caprinid rudist, *Offneria interrupta* Paquier, 1905 (left valve; note diagnostic absence of canals in mid-ventral margin, arrowed, *cf.* Paquier, 1905, Pl. XI, Figs. 15–17); b: middle member, bioclastic grainstone in massive clinoform bed; c: middle member, floatstone with *Chondrodonta* (ch) and rudists (ru); d: Casetas del Mayor, distal slope facies in lower limestones of Llopis Formation., containing rounded rudist rubble in grainstone matrix. All scale bars = 10 mm.

micritic platform-top biofacies characterized by drifts of modestly sized molluscs, including nerinellid, itieriid and other gastropods (Fig. 5d), small, thin-shelled rudists (Figs. 5e and 5f) and *Chondrodonta*, as well as solitary and small colonial corals, miliolid and orbitolinid foraminifers and dasycladacean algae.

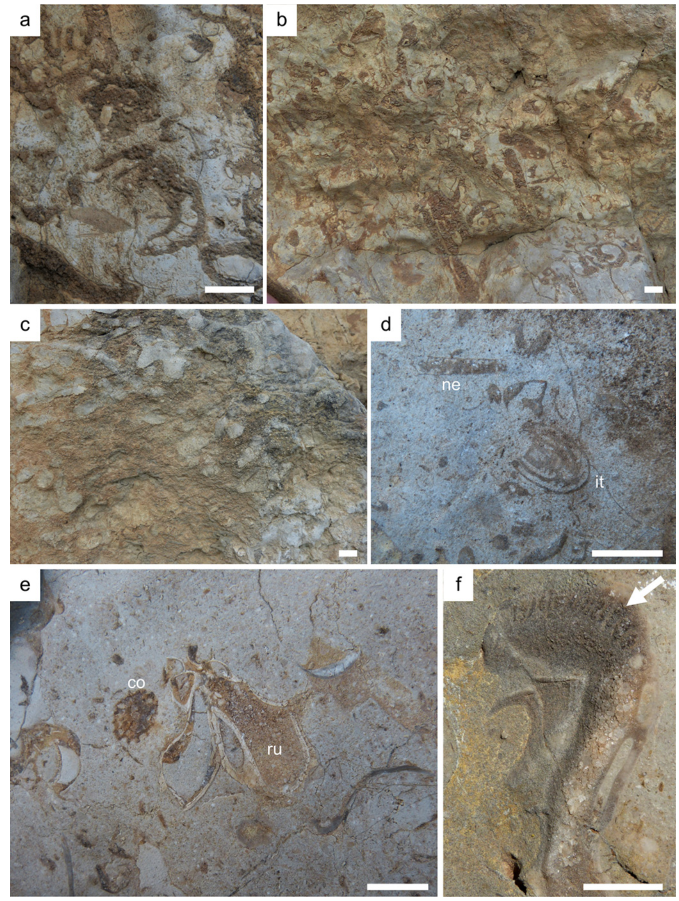

Fig. 5. Field views of platform-top facies at Llopis Farm locality, Sierra de Mariola: (a, b) vertical sections showing: a: rudist floatstone; and b: loose cluster of indeterminate elevator rudists preserved in upright life position; c: burrowed top of bed; (d-f) bed-top views of more internal platform-top beds, showing: d: nerineoid (probably nerinellid) (ne) and itieriid (it) gastropods (see Kollmann, 2014); e: small coral (co) and rudist (ru) debris; and f: fragment of small caprinid rudist, showing single row of simple marginal canals (arrowed), probably *Caprina douvillei* Paquier, 1905, left valve (see text for discussion). All scale bars = 10 mm.

2.1.2 Sierra de Seguilí

Some 40 km to the east, on the northern margin of the Sierra de Seguilí (Fig. 1b), a section through nearly 12 m of platform-top beds in the upper part of the Llopis Formation middle member is exposed alongside a small road south of the town of Benidoleig (Figs. 6a and 7a; Castro, 1998, section SEG 1b). Relatively easier access to, and better preservation of the strata here (Figs. 6b and 6c), compared to the Mariola exposures, allow more detailed analysis of their biofacies. This short succession shows an overall upward trend from floatstones of rudist, coral and other bioclastic debris, in a packstone to grainstone matrix (Figs. 7a–7c), to rudist-dominated floatstones, including some specimens preserved in

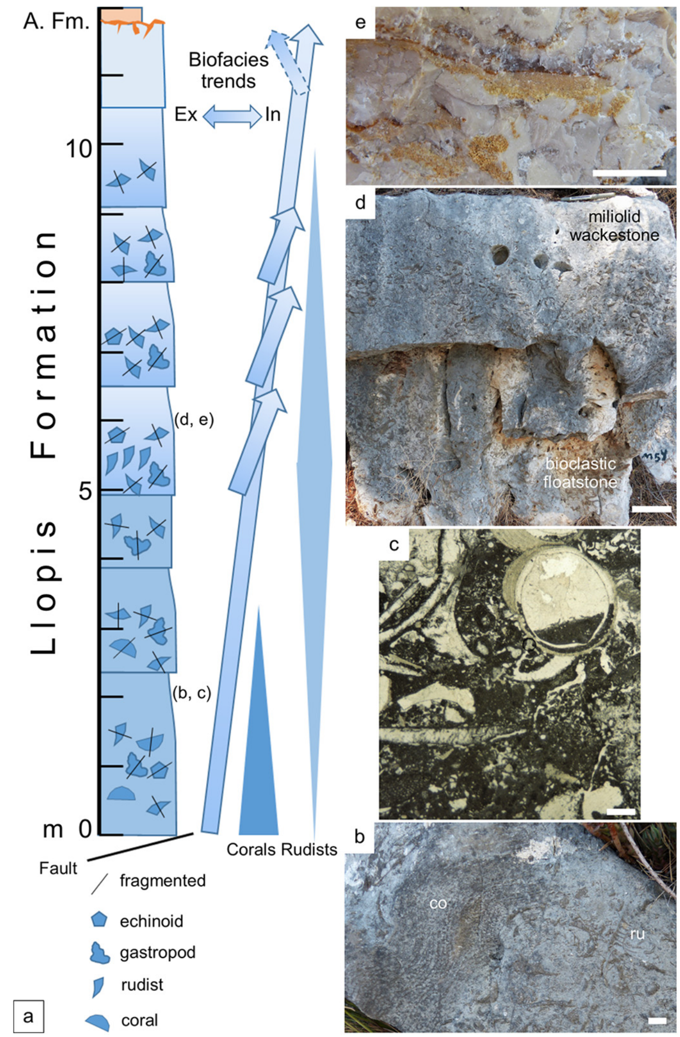

Fig. 7. Llopis Formation platform-top beds studied at Sierra de Seguilí: a: summary log of studied section showing overall, and bed-scale biofacies trends (External-Internal) up to boundary with overlying Almadich Formation (A. Fm.); b: exposure of rudist (ru) and coral (co) floatstone at 0–2.4 m in (a); c: thin section photomicrograph from lowest bed, showing *Bacinella* nodule containing orbitolinid and other bioclastic debris, and perforated by lined, geopetally filled bivalve borings; (d, e) upper half of bed at 5–6.5 m in (a), showing inferred regressive biofacies stacking (d), and (e) fractured vertical section through microkarstic cavities at top of bed, geopetally filled with orange-coloured crystal silt. Scale bars: b, e: 10 mm; c: 1 mm; and d: 100 mm.

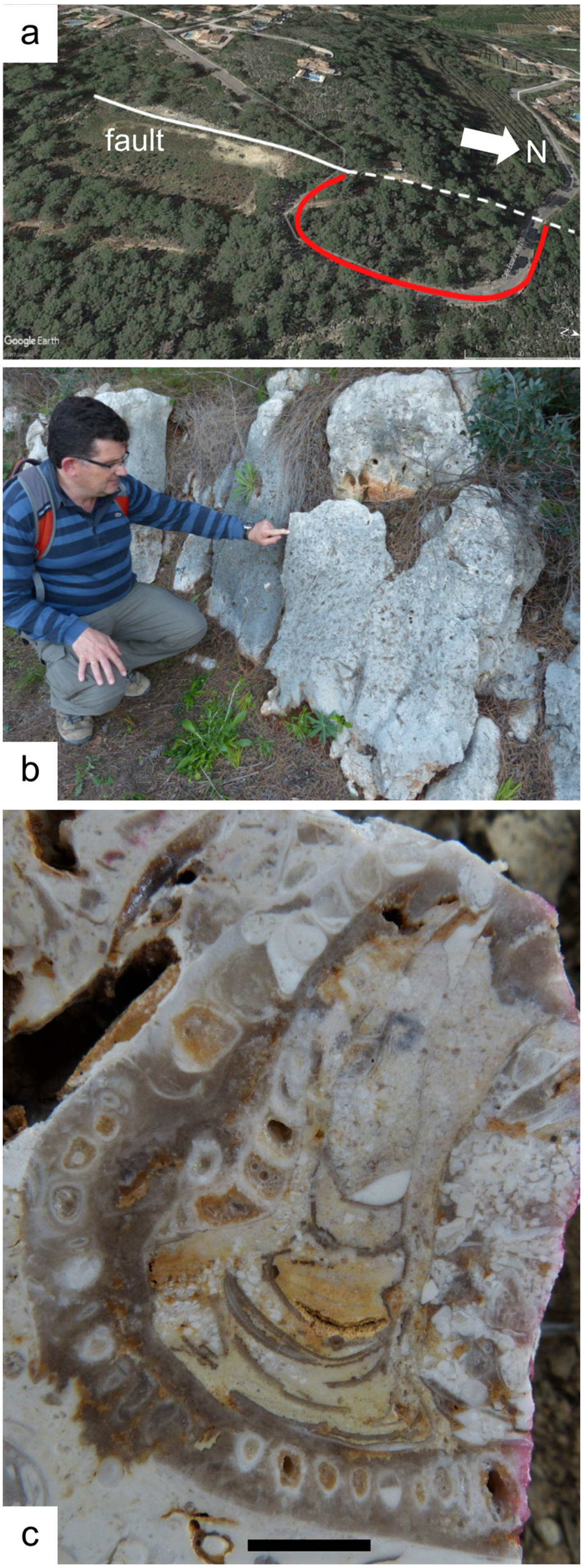

Fig. 6. Llopis Formation at Sierra de Seguilí (see Fig. 1 for location): a: situation of road section (bold red line) exposing platform-top beds; b: example of roadside exposure (= bed shown at 5–6.5 m in Fig. 7a); c: cut surface of block recovered from repeat section of upper beds to west of fault in (a), showing adumbonal view of postero-dorsal part of left valve of large *Offneria* sp., most likely O. *rhodanica* Paquier, 1905 (*cf.*, Paquier, 1905 Pl XII, Fig. 5), scale bar = 10 mm.

Fig. 8. Macrobiota in lower part of Llopis Formation section shown in Figure 7a: a: large colonial coral (co) of low domal form preserved in life position; b: coral and indeterminate gastropod fragments; c: nerineid gastropod; (d, e): caprinid rudists, d: *Offneria* sp., and e: left valve of probable *Caprina douvillei* (*Ca*, detail shown inset; see text for discussion) within main cavity of larger, indeterminate rudist valve. Scale bars: a: 100 mm; b–e: 10 mm.

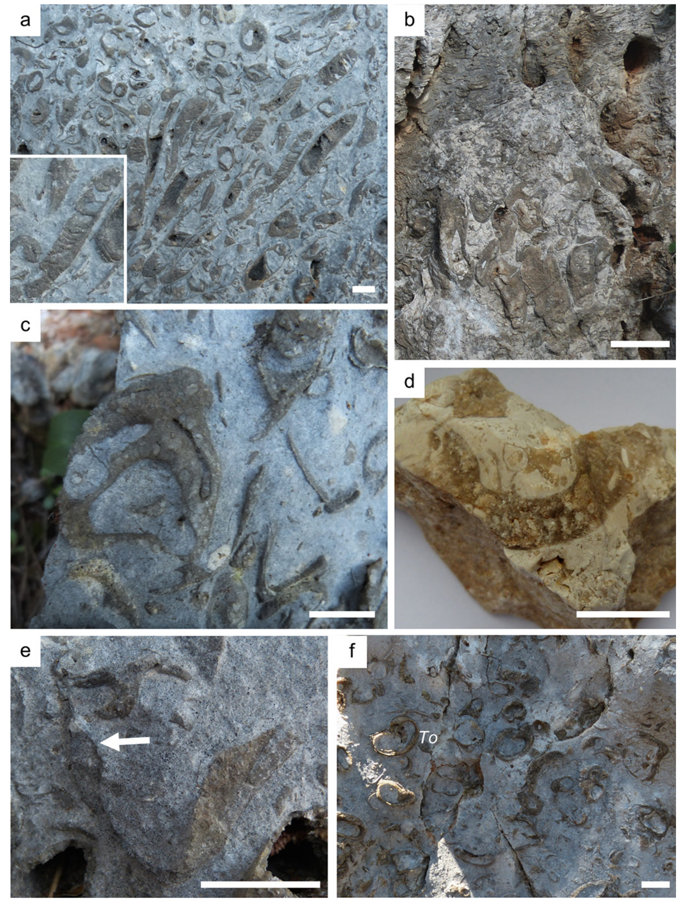

Fig. 9. Rudist floatstones in upper part of section shown in Figure 7a: a: tubular monopleurid shells dominant (probably *Mathesia*; inset shows detail of tabulae – see text for discussion), with cluster preserved in upright life position; b: cluster of robust caprinids (?*Pachytraga*, but too recrystallized for secure determination) preserved in upright life position, overlain by shell bed of horizontally oriented *Chondrodonta* (at top), in repeat section of upper beds to west of fault shown in Figure 6a; c: left valve of *Pachytraga paradoxa* (Pictet and Campiche, 1869; see Skelton and Masse, 1998); d: partial left valve of probable *Caprina douvillei* (see text for discussion); e: *Polyconites* aff., *hadriani* Skelton *et al.*, 2010 (polyconitid), section through articulated shell showing characteristic posterior myophoral arrangement at left, including inwardly inclined myophore in right (lower) valve (arrowed; see text for discussion); f: small *Toucasia* sp. (requieniid) (*To*), with other rudist debris. Scale bars: a, c-f: 10 mm; and b: 100 mm.

life position, in its upper part (Figs. 7a and 7d). We interpret this overall biofacies trend as broadly progradational, with the more disturbed, rudist/coral facies in the lower beds representing the more energetic external platform and the succeeding rudist-dominated beds having been more internally situated – in keeping both with the large-scale bedding and facies anatomy directly visible in the Sierra de Mariola, described above, and with the typical relative distributions of Cretaceous corals and rudists observed elsewhere (Skelton *et al.*, 1997). However, a possible short-term reversal to transgression is hinted at in the topmost part of the Llopis Formation here, which will be discussed in the next section (2.2).

Although most of the macrofossils in the lower beds are fragmented, bored and/or worn (Figs. 7b and 7c), a few large coral colonies of low domal form are preserved in life position (Fig. 8a). The accompanying biotic components in these lower beds include *Chondrodonta*, various gastropods (Figs. 8b and 8c), globose cidarid echinoid spines, bryozoans, calcareous sponges, orbitolinid and other benthic foraminifers, calcareous algae and *Bacinella* nodules (Fig. 7c), together with a few thinly coated ooids. The rudist complement of these beds – mostly disarticulated or fragmentary – is dominated by caprinids, especially the large canaliculate genus *Offneria* (Fig. 8d), but also including *Pachytraga* (see below) and a rarer, miniscule taxon with a single row of simple pallial canals of pyriform cross-section (Fig. 8e, *Ca*), most likely attributable to *Caprina douvillei* Paquier, 1905. Although Masse and Chartrousse (1997, p. 805) caution against confusing this latter species with the equally small *Offneria nicolinae* (Mainelli, 1983), we regard that identification as less likely in this case, as we have not, as yet, observed any examples here containing tabulae (cf., Figs. 5f and 9d). Relatively scarce fragments of other rudists include small tubular monopleurids (?*Mathesia*, discussed below) and *Toucasia*, both of which are more common in the overlying beds.

As at the Sierra de Mariola, the rudist-dominated tabular beds in the upper part of the Llopis Formation at Sierra de

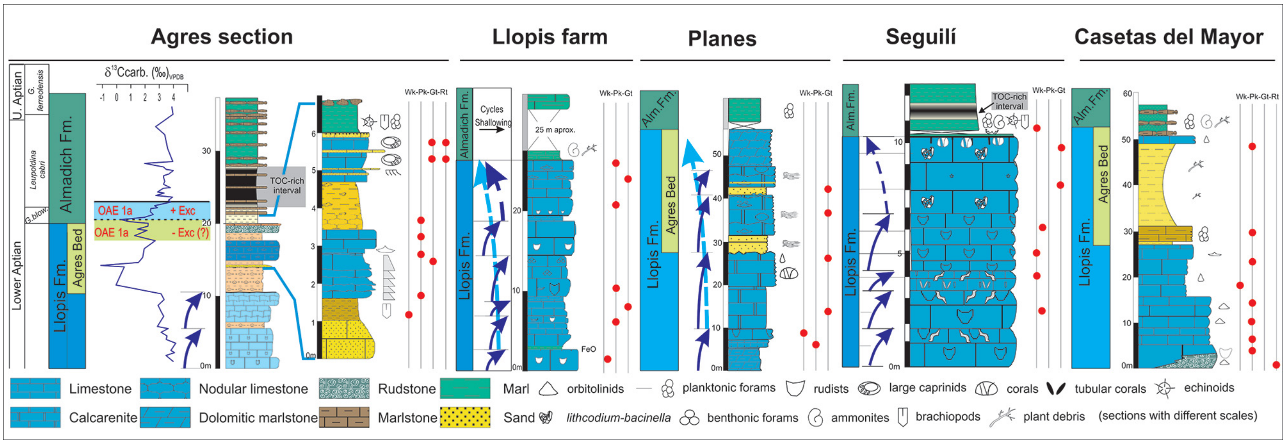

Fig. 10. Detailed logs of the termination of the Llopis Formation platform (Llopis-Almadich transition); carbon isotopic curve for the Agres section modified from Castro et al., 2014 (Fig. 2). See Figure 1 for section localities.

Seguilí show a cyclic stacking of biofacies (especially those from 5 m upwards on the log in Fig. 7a). Each bed consists mostly of closely packed floatstone, with a matrix of miliolid-rich bioclastic packstone, capped by miliolid-rich wackestones containing sparse macrofossils (Fig. 7d). We interpret these repetitively shallowing beds as representing successive minor regressive cycles – an interpretation supported in a few cases by the presence at their tops of microkarstic cavities with geopetal fills of orange-coloured crystal silt (Fig. 7e), indicating emergence.

Locally, clusters of elevator rudists are preserved in life position in the lower parts of these cyclic beds (Figs. 9a and 9b). Though caprinids are again common in this part of the section, especially *Pachytraga paradoxa* (Figs. 9b and 9c; see Skelton and Masse, 1998), together with *Offneria* spp., including both *O. rhodanica* Paquier, 1905 (Fig. 6c), and *O. interrupta* Paquier, 1905 (the latter according to Chartrousse, 1998, p. 84) and *Caprina douvillei* (Fig. 9d), they are here copiously accompanied by other rudists. Prominent among the latter is a slender tubular monopleurid (Fig. 9a), tentatively assigned to *Mathesia* sp., on account of its possession of tabulae, which are known in this genus (see later), but not as yet recorded in the externally similar *Debrunia* (Masse and Fenerci-Masse, 2009). However, we have not yet been able to confirm the presence in this form from the Llopis Formation of the diagnostic fine longitudinal tubes around the inner margin of the outer shell layer (Masse and Fenerci-Masse, 2010), hence, its tentative status (though it is worth noting that *M. darderi* (Astre, 1933) has been identified at Sierra de la Muela, to the west of the study area, in upper Barremian beds (Fenerci-Masse *et al.*, 2011). Also present is a small polyconitid (Fig. 9e) with a posterior myophoral organization approaching that of *Polyconites hadriani* Skelton *et al.*, 2010–notably showing a depressed inward inclination to the posterior myophore in the right (lower) valve, in contrast to the projecting inner rim of that seen in its putative ancestral genus, *Horiopleura* (Skelton *et al.*, 2010), even including the "slightly depressed" myophore noted in the figured type specimens of *H. brevis* (Masse and Fenerci-Masse, 2017). The requieniid clinger *Toucasia* (Fig. 9f) is relatively more frequent in some of the upper beds. The non-rudist bivalve *Chondrodonta* is common throughout the section, in at least one instance forming a dense shell bed of horizontally oriented valves capping rudist floatstone (e.g., Fig. 9b).

Thus, caprinid rudists, with robust, originally almost wholly aragonitic shells, dominate the external platform-top facies, while the relatively more internal facies contain a mix of monopleurid, polyconitid and requieniid rudists, all of which show slightly thicker development of the calcitic outer shell layer relative to caprinids, together with the caprinids. This pattern of rudist distribution on the platform top is consistent with that found in previous studies of Tethyan platforms of Early Aptian age (Fenerci-Masse, 2006; Skelton and Gili, 2012).

A thin, more siliciclastic-bearing upper member of the Llopis Formation is present only locally (for example, in the Agres section on the Sierra de Mariola; Fig. 2), showing some striking contrasts with the typical "Urgonian"-type facies of the main part of the formation described above. As this regionally variable upward passage from the Llopis Formation to the basal part of the Almadich Formation offers important clues to possible reasons for the demise of the Llopis Formation platform, we describe it in detail in the following section.

2.2 Termination of the Llopis Formation platform

The record of the termination of the Llopis Formation platform consists of a complex transition from the rudist-bearing shallow platform carbonates of the Llopis Formation to the marls and marlstones with ammonites of the Almadich Formation, with interesting lateral variations revealed by the different sections studied (Fig. 10).

2.2.1 *Seguilí section*

The topmost part of the Llopis Formation in this section presents an abrupt facies change, marked also by the disappearance of rudists (Fig. 10). The facies of the uppermost 2 m of the Llopis Formation here consists of fine-grained,

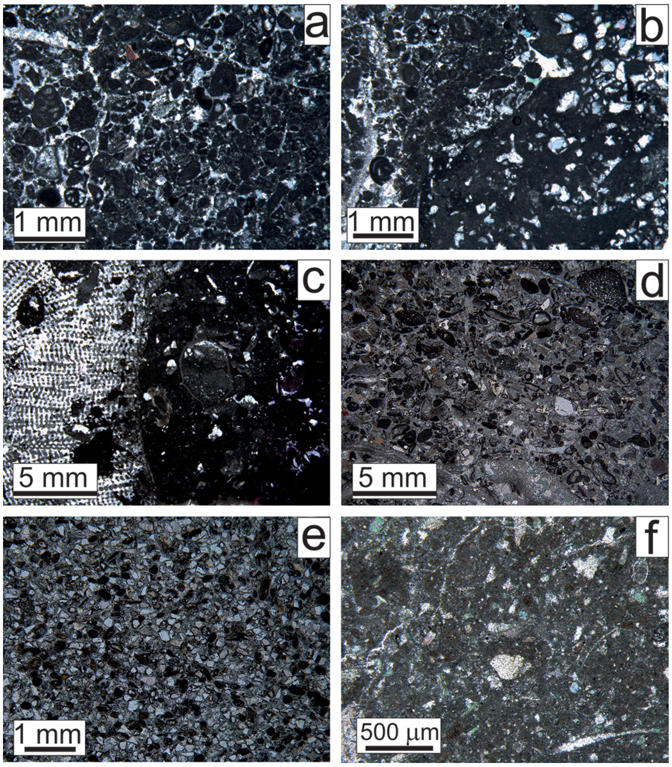

Fig. 11. Microfacies from top of Llopis Formation. (a-c) Seguilí section: a: fine grainstone with peloids, intraclasts and small benthic foraminifers; b: *Lithocodium-Bacinella* nodule embedded in fine grainstone; c: bored coral with micritic sediment and geopetal fillings. (d, e) "Agres bed", Agres section (see Fig. 10): d: poorly sorted bioclastic sandy grainstone; e: fine grained, well sorted, calcareous sandstone; f: silty bioclastic marl microfacies of Llopis/Almadich transition at Casetas del Mayor.

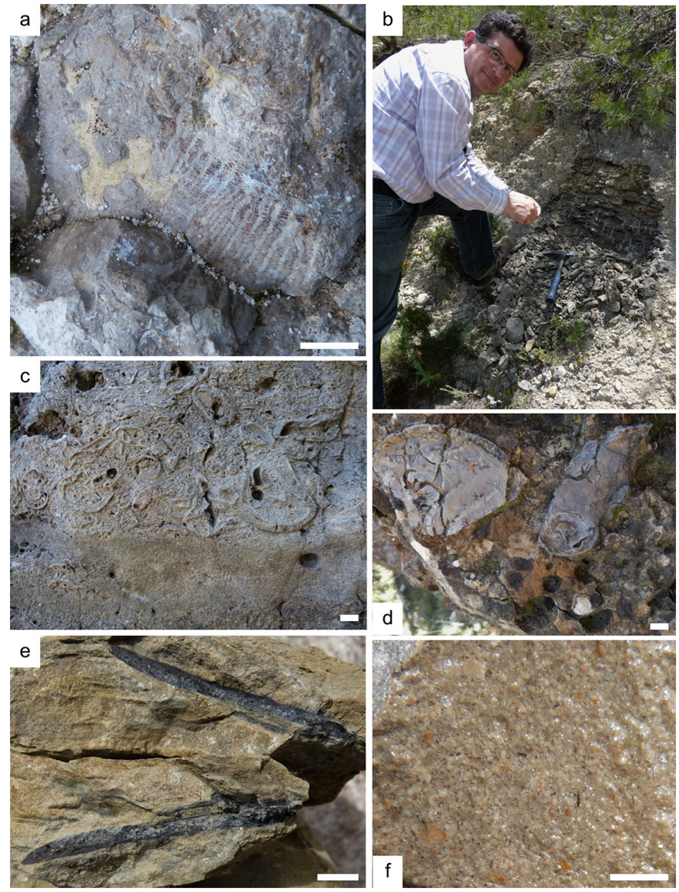

Fig. 12. (a, b) Sierra de Seguili: a: top surface of Llopis Formation, with bored and partially dissolved coral in hardground surface and; b: dark marl (above hammer) in basal Almadich Formation. (c, d) Llopis Formation upper member at Agres: c: calcarenite with caprinid rudstone above and; d: and oyster-encrusted firmground at top. (e, f) Terminal Llopis Formation facies at Casetas del Mayor: e: siltstone with plant fragments and; f: finely comminuted bioclastic grainstone of topmost bed. Scale bars: a, c–e: 10 mm; and f: 1 mm.

moderately sorted grainstones with peloids, intraclasts and small foraminifers (Fig. 11a), and some *Lithocodium-Bacinella* nodules (Fig. 11b). The uppermost bed has bored corals, embedded in micritic sediment with geopetal structures (Fig. 11c). The top surface of the section shows partially dissolved borings in the coral-rich level (Fig. 12a), is slightly irregular and is covered by a marly crust with ammonites and planktonic foraminifers. The marly basal part of the Almadich Formation is poorly exposed and, moreover, is locally obscured by a fault (Fig. 6a). Where the Llopis/Almadich boundary succession is preserved, a thin observational gap of a few cm is followed by a section of about 10 m of beige marls and marlstones with rare ammonites and containing a 65-cm thick level of darker grey shaley marl at its base (Figs. 10 and 12b). This facies succession is interpreted as the result of a change to more open marine conditions during the last part of the deposition of the Llopis Formation, with development of fine grainstones finally colonized by corals. The top surface indicates an interruption in sedimentation, with a probable episode of emersion, leading to the development of microkarst with geopetal sedimentary filling. After the interruption, sedimentation resumed in deeper open marine hemipelagic conditions, characteristic of the Almadich Formation. We suggest that the dark layer at its base may correspond to the lithologically similar interval in the lower part of the nearby, more basinward Cau section (Fig. 2), which has in turn been interpreted as an expression of OAE1a (de Gea *et al.*, 2003; Naafs *et al.*, 2016; Ruiz-Ortiz *et al.*, 2016).

2.2.2 *Mariola-Llopis farm section*

In this section, the uppermost beds (~25 m) of the Llopis Formation are limestones with rudists and orbitolinids, making part of a succession of shallowing upwards cycles that ends with a last cycle 7.5-m thick, with planar orbitolinids, crinoids, and less frequent bryozoans, *Lithocodium-Bacinella* and quartz (Fig. 10). The top is marked locally by a slightly ferruginous surface, passing laterally into a more gradual transition. The base of the Almadich Formation is a marlstone with planktonic foraminifers and some planar orbitolinids, together with some small irregular echinoids and terebratulide brachiopods and encrusting bryozoans, which grades upwards into marls and marlstones with ammonites. The sedimentary

Table 1. List of benthonic foraminifers and rudist bivalves from the Llopis Formation.

Benthic foraminifers	Rudist bivalves
Choffatella decipiens Schlumberger	*Offneria interrupta* Paquier (Fig. 4a)
Neotrocholina sp.	*Offneria rhodanica* Paquier (Fig. 6c)
Palorbitolina lenticularis Blumenbach	*Caprina douvillei* Paquier (Figs. 5f, 8e, 9d)
Orbitolinopsis [*O.*] *cuvillieri* Moullade	*Pachytraga paradoxa* (Pictet and Campiche) (Fig. 9c)
O. kiliani Silvestri	*Polyconites* aff. *hadriani* (Fig. 9e)
O. buccifer Arnaud-Vanneau & Thieuloy	?*Mathesia* sp. (Fig. 9a)
O. praesimplex Schroeder	*Toucasia* sp. (Fig. 9f)
O. pygmaea Arnaud-Vanneau	
Paracoskinolina maynci Chevalier	

evolution recorded in this outcrop is somewhat similar to that of the Seguilí section, with a reversal of the shallowing upward evolution of the Llopis platform in its uppermost part. The transition to the hemipelagic conditions marked by the Almadich do not show evidence for erosion, and the interruption is less marked, probably related to a gradual deepening across the Llopis-Almadich transition.

2.2.3 *Mariola-Agres section*

This section is located some 3.5 kms to the north of Llopis Farm, over an almost continuous outcrop in the same large anticline, so they are interpreted as having been separated palaeogeographically by approximately that distance. Notwithstanding the short distance between the sections, they present marked differences. In the Agres section, the Llopis Formation contains a new stratigraphic unit below the Almadich Formation, the 'Agres bed', defined as the upper member of the Llopis Formation (Castro, 1998) (Fig. 10). The uppermost part of the Llopis Formation middle member (some 10 m in outcrop), below the Agres bed, consists of well-bedded rudist limestones with bioturbated tops and wackestone-packstone textures. The Agres bed is composed of 10 m of calcarenites, calcirrudites with caprinids (mainly fragments of large *Offneria*; Fig. 12c), marls and sands (Figs. 11d and 11e), with some current structures, including hummocky cross-stratification. The top surface of this unit is a bored surface with encrusted ostreids (Fig. 12d), interpreted as a firmground formed during an interruption of sedimentation. The base of the Almadich Formation here is a 2-m thick level of brown marls with marlstones, followed by 4.5 m of dark marls enriched in TOC (maximum 0.55%, Castro *et al.*, 2014). The succession continues with an alternation of marls and marlstones with planktonic foraminifers and some ammonites, with a total thickness of 65 m up to the end of the outcrop. The C-isotope data show a negative peak at the base of the Almadich Formation of 0.3‰, followed by a positive excursion from 0.3 to 3.9‰ with highest values within the TOC-rich interval, together defining a Carbon isotope excursion (CIE), followed by a ~15 m interval with similar values (Fig. 10), then by a marked decrease up to the top of the Lower Cretaceous (Castro *et al.*, 2014). The lower part of the Almadich Formation in this section has been interpreted as the local expression of OAE1a (Castro *et al.*, 2014).

In this section, the most striking feature is the presence of the Agres bed, reflecting an important siliciclastic input at the termination of the platform, under high energy conditions, probably with deposition of storm beds. The facies changes recorded within the Agres bed indicate a complex evolution with different pulses of low energy (marls) and high energy (sandstones, sands, calcarenites, rudist rudstones), collectively indicating an open marine environment with mixed carbonate and terrigenous sediment sources. The top of this unit is a surface of sedimentary interruption, with borings and encrusting bivalves, marking a sharp change towards the overlying hemipelagic sediments of the Almadich Formation.

2.2.4 *Planes section*

This section is located 12 km to the east of Mariola and, although the carbonates of the Llopis Formation are irregularly dolomitized and the section is partly covered, it permits the observation of the upper part of the Llopis and the middle part of the Almadich Formations. The uppermost part of the Llopis Formation here records a transition from rudist floatstones to bioclastic grainstones with coral debris, which are capped by an erosional surface. On top of this surface, there is a 24-m thick unit of alternating sands and calcarenites (bioclastic grainstones with orbitolinids), both with hummocky cross-stratification (Fig. 10). This unit is interpreted as the local record of the Agres bed. Above a 10-m thick covered interval, the marls of the Almadich Formation crop out, and are dated as late Bedoulian (*L. cabri* biozone) from the content of planktonic foraminifers (Castro, 1998).

2.2.5 *Casetas del Mayor section*

This section is located in the Sierra del Carrascal de Parcent, 30 km to the East of the Sierra de Mariola (Fig. 2) and represents the most distal environments of those included in this study. In these outcrops (Fig. 10), the distal slope rudist rudstone in the lower part of the Llopis Formation mentioned in the previous section (2.1.1, Fig. 4d) is succeeded by a 30-m thick succession of packstones with some orbitolinids and bioclasts of bivalves, crinoids, and benthic foraminifers, with small amounts of quartz. The upper part of the Llopis Formation here is represented by an 18-m thick unit of silty marls with quartz, wood fragments (Fig. 12e) and some ferruginous concretions, followed by a 2-m thick level of fine-grained bioclastic grainstones (Fig. 12f) to packstones with orbitolinids, benthonic bioclasts, and scarce planktonic foraminifers. The transition to the Almadich Formation is a net facies change towards a rhythmic succession of pale brown micritic silty marlstones and marly limestones (Fig. 11f) with ammonites and planktonic foraminifers. In this area, the most distal of those studied here, there is no evidence of sedimentary interruption at the top of the Llopis platform but, similarly to other sections, there is evidence of a notable siliciclastic input predating the installation of the hemipelagic environments of the Almadich Formation.

2.2.6 The timing of the termination of the Llopis Formation and its correlation with the signature of OAE1a

The age of the Llopis-Almadich transition has been determined by reference to orbitolinid and rudist data from the Llopis Formation (Tab. 1), constrained by ammonites in its lowest part, and from the ammonites, planktonic foraminifers and calcareous nannofossils of the Almadich Formation. In combination, these data indicate an early Aptian (Bedoulian) age for the top of the Llopis Formation (Castro, 1998; Castro *et al.*, 2001).

While the youngest ammonites found in the lowermost beds of the Llopis Formation in the Sierra de Mariola can be assigned a Late Barremian, Feriaudianus Zone age (Castro 1998, p. 55: *Hemihoplites* cf., *feraudianus* d'Orbigny, *H.* cf., *soulieri* Matheron and *H. astarte* Fallot and Termier), the association at the base of the slightly more distal section of this formation in the Sierra de la Solana, immediately south-east of the Sierra de Seguilí, encompasses a terminal Barremian to earliest Aptian range in age (Castro 1998, p. 140: *Kutatissites* sp., *Ancyloceras* sp., *Procheloniceras* cf., *pachistefanum* Uhlig, *Pseudohoploceras* sp., and *Barremites strettostoma* Uhlig). So, although the orbitolinid and rudist taxa cited in Table 1 might otherwise be considered to allow a relatively broad Late Barremian to Early Aptian possible age bracket (e. g., Clavel *et al.*, 2013) for the middle to upper members of the Llopis Formation, the ammonite data cited above further constrain it to the Early Aptian.

The lower part of the Almadich Formation in the Sierra de Mariola has also been dated from ammonites (Busnardo *et al.*, 1968; Company *et al.*, 1982; Castro, 1998), which indicate an age corresponding to the *Deshayesites deshayesi* biozone (Charollais *et al.*, 1994; Reboulet *et al.*, 2011, 2014), i.e., the early part of the late Bedoulian. Data from the Casetas del Mayor section indicates a slightly older age for the base of the Almadich Formation in that section (from the presence of *Deshayesites cf. euglyphus*), corresponding to the *Deshayesites forbesi* biozone, and probably to its upper part, the subzone of *Roloboceras hambrovi* (according to Moreno-Bedmar *et al.*, 2009, 2012). More recent data on planktonic foraminifers (Castro *et al.*, 2014) show that the base of the Almadich Formation in the Mariola-Agres section belongs to the *Globigerinelloides blowi* biozone, consistently with the age obtained for the base of the Almadich in the Seguilí section (Castro, 1998). In addition, the boundary with the overlying *Leupoldina cabri* biozone is some 2.3 m above the base of the Almadich in the Agres section, where it marks also the base of the OM-enriched levels of the OAE 1a, and the base of the positive C-isotope excursion of this event (Fig. 10; Castro *et al.*, 2014).

Collectively, these data support a correlation between the termination of the Llopis platform and the onset of OAE1a (as now conventionally defined: e.g., Jenkyns, 2018). The Cau section, located 10 km to the south of the Seguilí section, and deposited in a more distal location within the Prebetic platform, records the complete Lower Aptian in the hemipelagic facies of the Almadich Formation (Castro, 1998; Aguado *et al.*, 1999), and has provided a distinctive C-isotope stratigraphy, with recognition of the isotope segments defined by Menegatti *et al.* (1998), (de Gea *et al.*, 2003; Moreno-Bedmar *et al.*, 2012; Naafs *et al.*, 2016; Ruiz-Ortiz *et al.*, 2016). This section reveals a coincidence between the base of the *L. cabri* biozone and the boundary between C-isotope segments C3-C4, which is in agreement with data from La Bédoule, in SE France (Lorenzen *et al.*, 2013). Hence, the termination of the Llopis platform occurred clearly before the beginning of the positive C-isotope excursion (C4 segment of Menegatti *et al.*, 1998) of OAE1a (Fig. 10) – consistently with the appearance of the dark shaley marls in the basal Almadich Formation a little above the top of the Llopis Formation in both the Mariola-Agres and Seguilí sections (Figs. 10 and 12b). This termination would thus probably have occurred during the C3 isotope segment, which has been estimated to have lasted about 300 ky (e.g. Huck *et al.*, 2011; Hu *et al.*, 2012), although other authors have proposed a shorter interval, of 22 ky to 44 ky (Li *et al.*, 2008; Malinverno *et al.*, 2010). Therefore, further investigations are needed to increase the precision of our correlation, to establish the time interval that elapsed between the termination of the Llopis Formation and the initiation of the C-isotope positive excursion. It is worth noting that this time interval is coeval with a pulse in the extensional tectonics that affected the SIP (Martín-Chivelet *et al.*, 2002). Block-tilting could thus have given way to new depocentres where terrigenous sediments preferentially accumulated, while at the same time, the higher parts became emergent. All this would have resulted in the lateral differences detected in the record of the Llopis-Almadich transition. This event has been widely recorded in the Tethyan and proto-Atlantic domains (e.g. Millán *et al.*, 2009; Najarro *et al.*, 2011; Masse and Fenerci-Masse, 2011, 2013a, 2013b; Moreno-Bedmar *et al.*, 2012, 2014; Frau *et al.*, 2017; among others), but the precise dating and correlation is still a matter of discussion and ongoing research (e.g. Frau *et al.*, 2017).

3 Late Aptian to Early Albian Seguilí platform

The Almadich Formation passes upward to a second major carbonate platform development in the Alicante region. The first step of progradation took place in the mid-Gargasian, corresponding to the top of the *E. subnodosocostatum* ammonite biozone (Fig. 2; Castro *et al.*, 2008). Three main phases of carbonate platform development are recorded from the mid-Gargasian up to the earliest Albian (Figs. 2 and 13; SF-1 to SF-3). They comprise two over-stepping progradational sequences (in the mid-Gargasian and mid-Clansayesian), succeeded by a retrograded progradational sequence, all three recorded in the Seguilí and Carrascal de Parcent areas as a multi-phase carbonate platform (Fig. 13). The last sequence is coeval with a stratigraphic discontinuity in the Sierra de Mariola section (Fig. 2), probably extending towards the more proximal sectors of the Prebetic platform (Castro, 1996; Castro *et al.*, 2008).

The first step of progradation over the hemipelagic sediments of the Almadich Formation in the Sierra de Seguilí is recorded by a transition from nodular marly limestones with sparse ammonites and irregular echinoids to pale buff sandy limestones with orbitoline fragments (Fig. 13, SF-1; Fig. 14a)

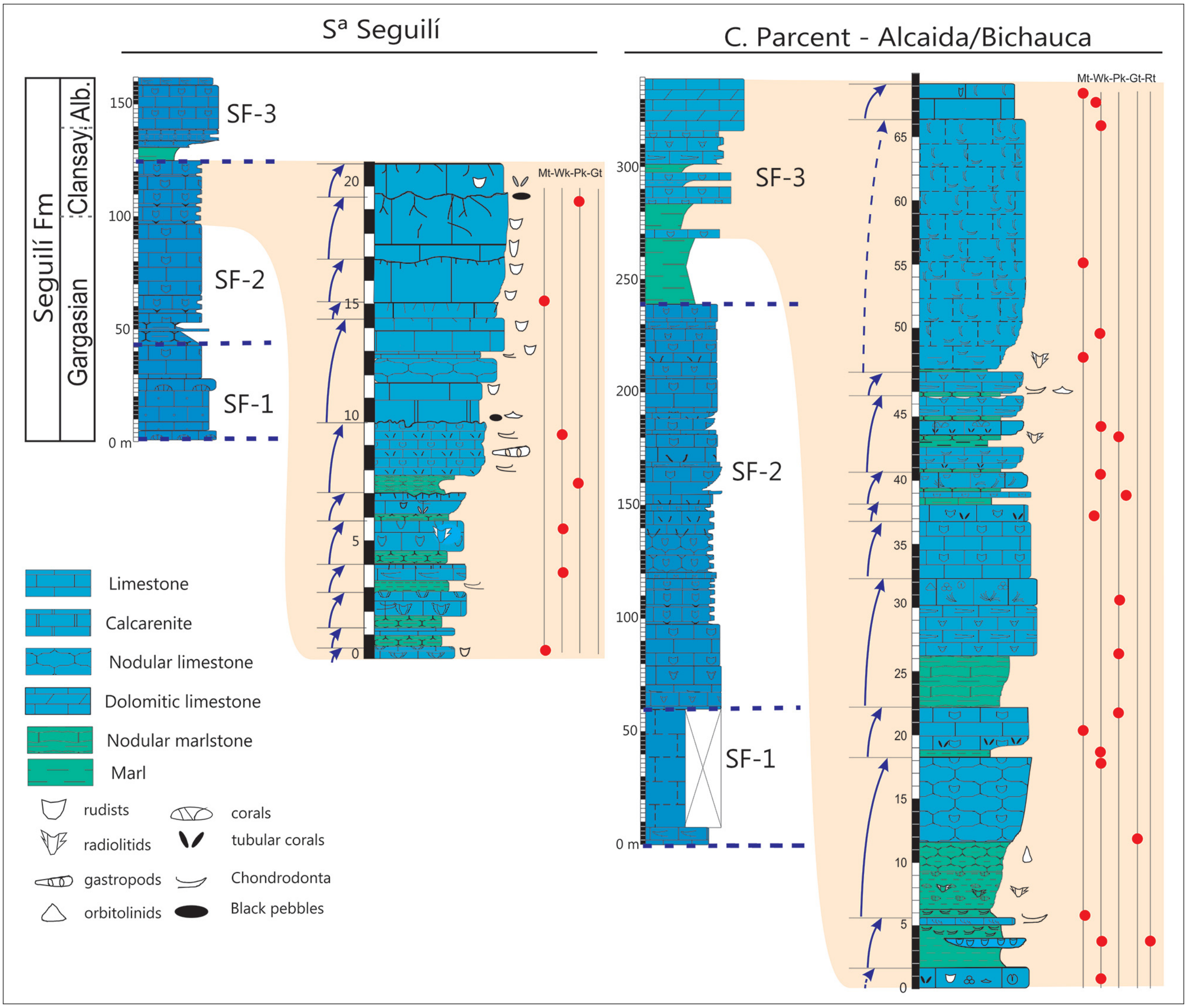

Fig. 13. Summary logs for Seguilí Formation in the Sierra de Seguilí and the Carrascal de Parcent, showing the three successive sequences of platform development, with details of the sections studied in this work. See Figure 1 for locations of sections.

in which first corals, then rudists re-appear. Likewise, coarse coral and other bioclastic debris herald the progradation of the third, youngest sequence in the Barranco de Alcaida (Fig. 13, SF-3; Fig. 14b). And as in the lower Aptian Llopis Formation platform, tabular platform-top beds again show a pattern of repeated cyclic regression, involving dense rudist and/or chondrodont floatstones (e.g., Figs. 14c and 14d), with localized shell clusters preserved in life position (Figs. 15a–c, 16a and 16b,), overlain by sparser floatstones with miliolid-bearing wackestone matrix, including micro-geopetal structures (Figs. 14e and 14f) and in some cases burrows containing secondary orange-stained fills suggestive of emersion (e.g., Fig. 15d).

Nevertheless, in the Seguilí Formation platform successions, the facies associations are more variegated, with the appearance of marly nodular levels in the basal parts of the cycles, infilling underlying burrows (Fig. 16e), and the development of microkarst, breccia and black pebble horizons in parts of the succession. These last-named features mark the maximum regression intervals, which heralded the initiation of the successive episodes of carbonate platform development, considered as third-order depositional sequences by Castro *et al.* (2008). Also, characteristic of the Seguilí Formation is the greatly increased development of *Chondrodonta* biofacies, relative to the Llopis Formation. This biofacies is made of dense clusters of these large bivalves, with thick, oyster-like foliaceous calcite shells (Fig. 14d), which show repeated cycles of accumulation of horizontally oriented shells followed by vertically organized shells, embedded in wackestones (Figs. 16a and 16b), with a similar growth fabric to those described by Posenato *et al.* (2018) from the lower Aptian of the Gargano Peninsula in SE Italy. This type of facies is best developed and shows larger specimens in the Clansayesian and lowermost Albian levels, and has also been described in sections from the upper Aptian of the Basque-Cantabrian basin (Gómez-Pérez *et al.*, 1999; Millán *et al.*, 2014). Nevertheless,

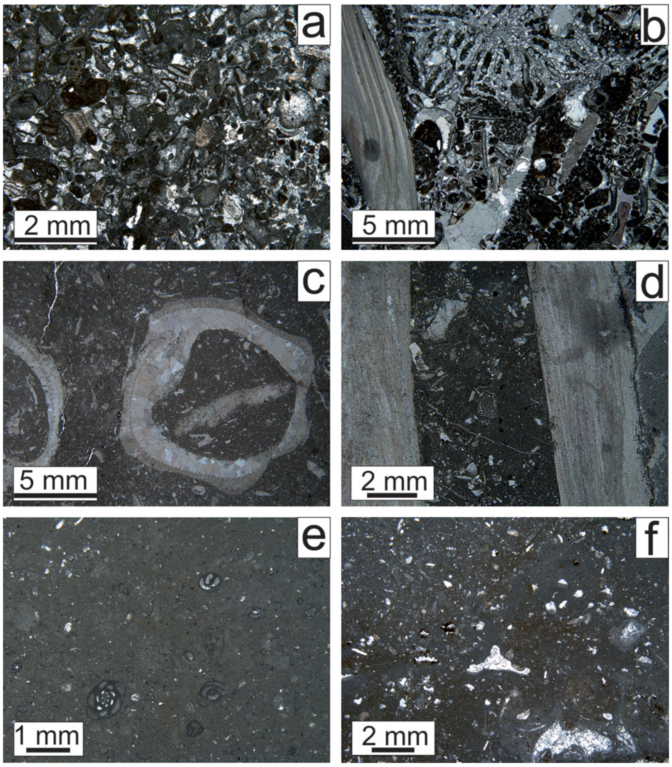

Fig. 14. Seguili Formation microfacies (see Fig. 13 for section details): a: fine-grained bioclastic-intraclastic grainstone with orbitoline fragments. Seguilí section, lower part of SF-1; b: coarse, poorly sorted bioclastic rudstone with corals, bivalves, peloids and intraclasts. Carrascal de Parcent section, lower-middle part of SF-3; c: floatstone with rudists (*Mathesia*); matrix is wackestone with miliolids and small bioclasts. Carrascal de Parcent section, middle part of SF-2; d: floatstone with *Chondrodonta*; matrix is wackestone with *Simplorbitolina* and small bioclasts. Carrascal de Parcent section, upper part of SF-3; e: wackestone with miliolids. Seguilí section, upper part of SF-2; f: wackestone with micro-geopetal structures. Seguilí section, lower middle part of SF-2.

the most prominent macrofossils in the Seguilí Formation are rudists, though with a strikingly altered cast with respect to the lower Aptian examples: thus, caprinids, previously so prominent, are now absent, while large requieniids (e.g., *Pseudotoucasia santanderensis* [Douvillé, 1889]; Figs. 16c and 16d) and polyconitids (*Polyconites verneuili* [Coquand, 1865; Fig. 16f]), as well as smaller radiolitids (e.g., *Eoradiolites* sp., Fig. 16g), all with appreciably thickened calcitic outer shell layers, accompany the remaining tubular monopleurid, *Mathesia darderi* (Astre, 1933) (Figs. 14c and 15c).

4 Discussion

In this section, we summarise similarities and contrasts between the Llopis and Seguilí Formations, as described above, especially with respect to their rudist associations (4.1). In 4.2, we draw parallels with co-eval examples from other parts of Iberia and contiguous regions and then briefly survey other Iberian platform successions that are intermediate in age between the two formations, during which time only hemi-pelagic deposits of the Almadich Formation were being deposited in the study area (Fig. 2), in order to gain a fuller picture of the changes in Iberian carbonate platforms during the Aptian. Finally, in 4.3, we discuss the possible causal factors that could have been involved in the macrofaunal turnover.

4.1 Comparison of Aptian carbonate platforms in the Alicante region

To a first approximation, carbonate platform progradation in the Llopis and Seguilí Formations resulted in essentially the same biofacies anatomy: massive bioclastic slope deposits with largely transported rudists, corals and associated biota were succeeded by tabular platform-top beds, each up to a few metres thick and dominated by rudists – though with *Chondrodonta* also especially prominent locally, especially in the upper parts of the Seguilí Formation. In both cases, most of the platform-top beds show a repeated regressive cyclicity, each bed commencing with more or less dense floatstone containing parautochthonous to autochthonous rudist associations – comprising mainly elevators with some clingers – in a predominantly packstone matrix, passing up to a thin cover of much sparser floatstone with a miliolid-rich wackestone matrix. This cover facies may be penetrated by burrows secondarily filled by contrasting matrix and/or microkarstic deposits. Larger, thick-shelled rudists tend to dominate in the floatstones of the more external platform-top biofacies.

The main difference in detail between the two formations emerges from analysis of the taxonomic make-up of their rudist associations. Whereas diverse caprinids overwhelmingly dominate the outer platform-top facies of the Llopis Formation platform, they are entirely absent from the Seguilí Formation platform. On the other hand, radiolitids, which are absent from the Llopis Formation platform, are moderately common and widely distributed across the younger platform. Meanwhile, although clusters of the slender elevator monopleurid, *Mathesia*, together with polyconitids and requieniids, as well as the non-rudist bivalve *Chondrodonta*, are moderately common across the Llopis Formation platform-top, they are all relatively more abundant on the Seguilí Formation platform, in which they also show increased mean shell size relative to their Llopis Formation predecessors – especially with the appearance of the large sediment-clinging requieniid *Pseudotoucasia* (Fig. 16c).

4.2 Aptian carbonate platform development beyond the Alicante region

The same overall pattern of biotic turnover from the Early to the Late Aptian has been documented in carbonate platforms in other parts of Iberia and contiguous regions (Masse, 1989; Masse *et al.*, 1998; Skelton, 2000; Fenerci-Masse, 2006; Skelton and Gili, 2012). In the southern Lusitanian Basin of Portugal, for example, the outer platform-top facies of the Ponta Alta Member of the Crismina Formation, of earliest Aptian (early Bedoulian) age, contains abundant and diverse caprinids, (Skelton and Masse, 1998; Burla *et al.*, 2008; Huck

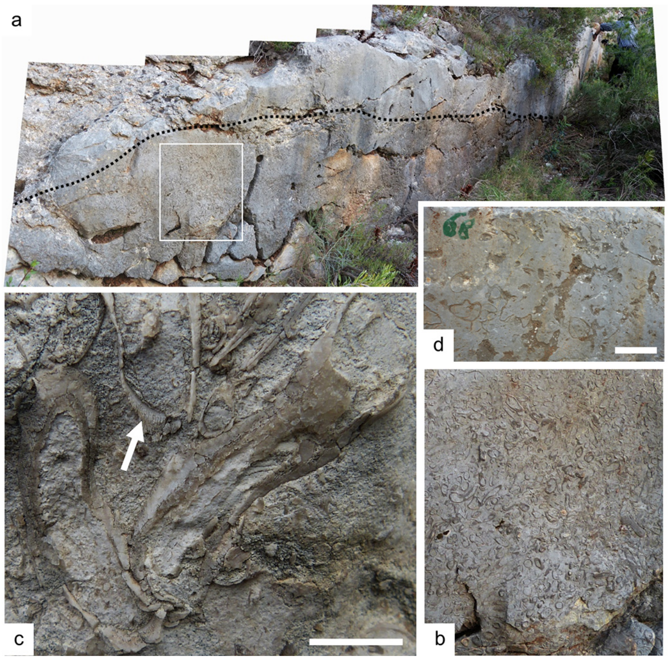

Fig. 15. Field photographs of platform-top bed in the Seguilí Formation (upper part of SF-2) in the Sierra de Seguilí (see Fig. 13 for section details): a: panoramic view of vertical section of bed, with crest of *Mathesia* cluster outlined by dotted line; b: detail of autochthonous *Mathesia* cluster (= white rectangle in (a)); c: close-up view of mutually attached right valves of *Mathesia darderi* (Astre, 1933) preserved in life position (arrow indicates eroded section of diagnostic fine canals at inner margin of outer shell layer; see Fenerci-Masse *et al.*, 2011); d: detail of wackestone at top part of bed (under man's hand at top right in (a)), with scattered large requieniids and burrows secondarily filled from above by orange-stained sediment. Scale bars: c: 10 mm; d: 100 mm.

et al., 2014), similar to those of the co-eval Llopis Formation. Meanwhile, though rudists are not mentioned from the coral-bearing Umbrera Formation in the northern Spanish Basque-Cantabrian Basin, García-Mondéjar et al. (2015a, 2015b) describe these shallow-water calcarenites as being overlain by ammonite-rich marly facies of the Patrocinio Formation, the first metres of which record the C3 to C6 segments of Menegatti *et al.* (1988). Thus, as with the Llopis Formation, the termination of the Umbrera Formation likewise predated the positive excursion phase of OAE1a. Although García-Mondéjar *et al.* (2015b, p. 8) caution that "There is no positive faunal evidence of a *Deshayesites oglanlensis* Zone age for the Umbrera Formation in the absence of ammonites", they note that "However, correlation of the geochemical data with the sections in Aralar, which contain ammonites of this age, support strongly an *oglanlensis* Zone age (García-Mondéjar *et al.*, 2009)".

Further north, the distal platform-top facies of the "U2" Urgonian limestones in the North Provencal Platform likewise contains a rich and diverse caprinid fauna (Masse and Fenerci-Masse, 2011), while requieniids and monopleurids are distributed throughout the platform interior facies – though a recent revision of the ammonite biostratigraphy of that region re-assigns these U2 limestones to the *Martelites sarasini* Subzone of latest Barremian, rather than earliest Bedoulian age (Frau *et al.*, 2018).

On the other hand, platform deposits of Late Aptian (to earliest Albian) age, entirely lacking caprinids, but with large requieniids (especially *Pseudotoucasia*) and polyconitids, as well as monopleurids and radiolitids, have been recorded from numerous localities elsewhere in Iberia, for example from Portugalete (Bilbao), as described in the classic palaeontological account of Douvillé (1889), to the Maestrat Basin in NE Spain (Malchus, 1998), as well as in SE Spain, in relatively more proximal settings to the north and west of the present study area (Masse *et al.*, 1998).

Of special interest in the present context, however, are Iberian platform successions of late Bedoulian age – hence intermediate in age between the Llopis and Seguilí Formations – that have been described from outside the present study area. These examples, particularly those situated within, or partly within the *furcata* Zone, reveal a transitional phase between the typical early Bedoulian (and/or latest Barremian), and the Late Aptian rudist faunas discussed above. Compared with the early Bedoulian examples, they show a significantly increased abundance of polyconitids in the outer platform-top to upper slope facies at the expense of caprinids, which, though still present, appear to have become more localized prior to their "Lazarus"-style disappearance at the close of the Bedoulian (Skelton and Gili, 2012). Again, examples may be cited from across northern Spain as well as in more proximal successions in south-eastern Spain.

In the Galve sub-basin of the western Maestrat Basin in northeastern Spain, for example, the marginal and upper slope facies of platform sequences within the Villarroya de los Pinares Formation are dominated by dense clusters of the founding species of *Polyconites*, *P. hadriani*, accompanied by corals (Bover-Arnal *et al.*, 2010; Skelton *et al.*, 2010; Gili *et al.*, 2016). Caprinids, meanwhile, have a more localized and restricted distribution in the region (Bover-Arnal *et al.*, 2015). A similar situation is encountered in the Basque-Cantabrian Basin in northern Spain (Aralar, Sarastarri Formation, Millán *et al.*, 2009; Mount Pagasarri, Peñascal Formation, Fernández-Mendiola *et al.*, 2017), where *P. hadriani*, and requieniids are again abundant, but caprinids limited to a few horizons within thick outer platform-top successions. In the carbonate platform succession of late Bedoulian age studied by Masse *et al.* (1998; 2015) in more proximal parts of the Prebetic margin to the west of the study area, caprinid-bearing facies likewise are shown in their logs to be relatively limited in extent (e.g., in El Carche and Sierra Larga; Masse *et al.*, 2015, fig. 2) – again accompanied by *P. hadriani*, which continues abundantly into the Gargasian.

To summarise, in Iberian carbonate platforms, caprinids, with largely aragonitic shells (having a calcitic outer shell layer of only sub-millimetric thickness; Skelton and Gili, 2012) dominated external platform-top rudist associations in the latest Barremian and early Bedoulian, but they were replaced by a consortium of large-shelled requieniids, polyconitids and radiolitids, together with *Chondrodonta*, all with relatively thicker (few to several mm) calcitic outer shell layers, in the Late Aptian. This turnover was mediated in the late (especially latest) Bedoulian, by a phase of carbonate platform development in which caprinids, though still present, became more restricted in distribution, while polyconitids and requieniids, particularly, proliferated.

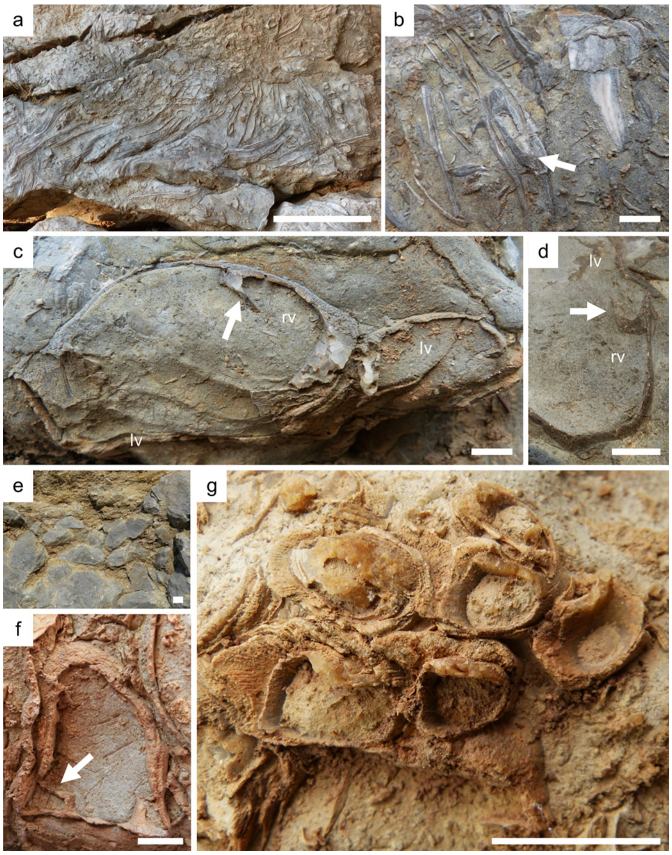

Fig. 16. Field photographs of platform-top facies and macrofauna in the upper part of the Seguilí Formation (SF-3), in the Barranco de Alcaida section (Carrascal de Parcent; see Fig. 2 for location and stratigraphical details): a: cluster of *Chondrodonta* shown in vertical section, preserved in inclined upright life position in bioclastic packstone matrix; b: close-up of vertical *Chondrodonta*, showing diagnostic under-folded chondrophore (arrowed); c: vertical section through attached left valve (lv), plus sliver of right valve (rv), including diagnostic posterior myophore (arrowed), of *Pseudotoucasia santanderensis* (Douvillé, 1889), preserved in life position in nodular marly bioclastic packstone in lower part of a cyclic bed; d: detail from section across commissure of another specimen of *P. santanderensis*, showing posterior myophore in rv; e: vertical section through wackestone to sparse packstone top of a cyclic bed, with burrows secondarily filled with marl from base of overlying bed; f: overturned articulated specimen of *Polyconites verneuili* (Coquand, 1865), with posterior myophore of right valve indicated by arrow, in bioclastic packstone matrix; g: small, overturned cluster of *Eoradiolites* sp., in bioclastic packstone matrix.

4.3 Controls on platform-macrofaunal turnover

The lower, and upper Bedoulian carbonate platform developments described above are stratigraphically distinct. The evidence relating to the demise of the Llopis Formation platform was detailed in the section on "Termination of the Llopis Formation Platform" (2.2). While regionally varying successions across the Llopis/Almadich boundary – including evidence for emersion in some places but not in others, as well as a locally additional sequence in the Mariola-Agres section (Fig. 10) – indicate some tectonically induced differences in accommodation, the general correlation of the Llopis/Almadich transition with the geochemical signature for the onset of OAE1a is remarkable. The siliciclastic influx locally preserved at the top of the otherwise carbonate-dominated succession of the Llopis Formation platform, moreover, suggests a climatic shift in this region from arid to relatively more humid/pluvial conditions in the late Bedoulian. A similar climatic change has been inferred for the same stratigraphical level in the southern Lusitanian Basin, and in the Algarve in Portugal (Burla *et al.*, 2008; 2009), while Bover-Arnal *et al.*, (2011) attributed a widespread horizon of storm-generated coral rubble beds in the Maestrat Basin, again correlative with the onset for OAE1a, to intensified greenhouse conditions with associated acceleration of the hydrological cycle. Such was the climatic context from which the late Bedoulian phase of platform recovery evidently took place, with the characteristic transitional rudist associations in Iberia cited above. Meanwhile, on some central to southern Tethyan platforms, by contrast, caprinids retained their dominance of outer platform-top environments through most if not all of the late Bedoulian – most notably, for example, in the Shu'aiba Formation of eastern Arabia (Hughes, 2004; Skelton and Gili, 2012), succeeding the HST of the Hawar transgressive-regressive cycle, with which OAE1a is most likely correlatable (Granier and Busnardo, 2013). This broad palaeolatitudinal differentiation of rudist associations that is apparent within the Tethyan belt is strongly suggestive of a continuing climatic control, whether exerted through thermal modulation of seawater pH and/or aragonite saturation (the "kettle effect" of Skelton and Gili, 2012), variation in nutrient flux (Föllmi, 2012), or – perhaps most plausibly – a combination of these influences. That the distributions of individual Early Cretaceous rudist genera were indeed susceptible to climatic influence has already been demonstrated by Masse and Fenerci-Masse (2008).

Nevertheless, hypotheses that seek to link biotic turnover with global environmental changes rely crucially upon both sound stratigraphical correlation and adequate geographical sampling (Skelton *et al.*, 2012). The recently revised dating by Frau *et al.* (2018) of the classic "U2" rudist limestones in the North Provencal Platform, from a previously supposed early Bedoulian age (Masse and Fenerci-Masse, 2011) to the latest Barremian, thus requires critical consideration. Even if this age re-assignment (based on the evidence of two ammonite specimens from the overlying "U3" limestones) is confirmed, together with rigorous verification of the total ranges of the two taxa concerned, *Pseudocrioceras* sp., and *Martelites* sp., there is no justification as yet for extrapolating this revised dating to the Iberian examples discussed in this paper. However, further testing of our current stratigraphical data, hence, our broader interpretation of events, should be pursued.

5 Conclusions

The Aptian stratigraphic record of the internal Prebetic zone in the Alicante region consists of three formations:

- the Llopis Formation, of earliest Aptian age, comprising shallow marine limestones with rudists and corals, locally with a thin siliciclastic member at its top;

- the Almadich Formation, of late Early, to Late Aptian age, composed of ammonite-bearing hemipelagic marls and marlstones;
- the Seguilí Formation, of Late Aptian to earliest Albian age, with shallow marine limestones again containing rudists and corals. The Almadich Formation, records a longer time interval towards more distal, southern locations.

In the Llopis Formation, carbonate platform progradation is recorded by SW-dipping, massive clinoform beds of bioclastic debris that are succeeded by flat-lying platform-top beds. The latter show a cyclic stacking of biofacies, with rudist-dominated floatstone in their lower parts, including local clusters of slender elevator rudists preserved in upright life position, passing upwards to finer-grained, more sparsely fossiliferous bed tops, which may show burrow mottling. These beds are interpreted to represent minor regressive cycles. Similarly to other co-eval Tethyan platforms, caprinid rudists, with originally almost wholly aragonitic shells, dominate the external platform-top facies, while the relatively more internal facies contain a mix of monopleurid, polyconitid and requieniid rudists, all with relatively slightly thicker development of the calcitic outer shell layer, together with caprinids. Biostratigraphic and carbon-isotope data support a correlation between the termination of the Llopis platform and the onset of OAE1a, co-incident also with a pulse in extensional tectonics affecting the Southern Iberian Palaeomargin.

Building-out of the Seguilí Formation carbonate platform over the hemipelagic Almadich Formation took place in three steps (sequences), during the Late Aptian to earliest Albian. As in the Llopis Formation, tabular platform-top beds again show a pattern of repeated cyclic regression, involving dense rudist and/or chondrodont floatstones, with localized shell clusters preserved in life position, overlain by sparser floatstones with wackestone matrix and secondarily filled burrows. Although the most prominent macrofossils in the Seguilí Formation are, again, rudists, caprinids are now absent, while requieniids and polyconitids, some of large size, as well as radiolitids, all with appreciably thickened calcitic outer shell layers, accompany the remaining tubular monopleurid, *Mathesia*. The development of *Chondrodonta* biofacies is also notably greater than in the Llopis Formation.

The same overall pattern of biotic turnover from the Early to the Late Aptian has been documented for carbonate platforms in other parts of Iberia and contiguous regions. Additionally, Iberian platforms of late Early Aptian age outside the present study area – hence intermediate in age between the Llopis and Seguilí Formations – reveal a transitional phase between these successive rudist faunas. Compared to the earliest Aptian examples, they show an increasing abundance of polyconitids in the outer platform-top to upper slope facies at the expense of caprinids, which became more localized prior to their "Lazarus"-style disappearance at the close of the Early Aptian.

The siliciclastic influx locally preserved at the top of the Llopis Formation platform implies a climatic shift from arid to relatively more humid/pluvial conditions through the mid-Early Aptian, similar to that inferred for several other Iberian sections. The co-incidence of this climatic change with the onset of OAE1a suggests that the former may be attributable to acceleration of the hydrological cycle forced by intensified greenhouse conditions. By contrast with the Iberian platforms, the outer platform-top zones of some central to southern Tethyan platforms remained dominated by caprinids until the close of the Early Aptian. This broad palaeolatitudinal differentiation of the turnover of rudist associations within the Tethyan belt is strongly suggestive of climatic influence, whether exerted through thermal modulation of seawater pH and/or aragonite saturation, variation in nutrient flux, or a combination of these.

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